

A simple criterium for CP conservation in the most general 2HDM

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Abstract

We find set of necessary and sufficient conditions for CP conservation in the most general 2HDM in terms of observable quantities. This set contains two relatively easily testable simple conditions instead of usually discussed three more complex ones.

1 Introduction

CP violation is one of the important yet not well understood problems in the fundamental physics. Modern LHC data [1] allow to conclude that the observed particle $h(125)$ is Higgs boson with spin-CP parity 0^{++} only under assumption that this particle has definite parity. Generally it can have no definite parity, as it happens in many models. In this case mentioned data give no information about $h(125)$ parity [2].

In the Standard Model the CP violation is described by means of CKM matrix, but its origin remains unclear. The extension of SM with two Higgs doublets instead of one as in the SM, called Two Higgs Doublet Model (2HDM), has been introduced in 1974 with the main aim for providing an extra source of CP violation [3]. If this violation realizes, the physical spinless particles have no definite parity (and CP).

The 2HDM, as many models of New Physics beyond SM, contains many new particles and interactions. A problem arises how to check in a simple way whether this model respects CP symmetry. This is the problem which is discussed in this paper.

2 2HDM

The 2HDM describes a system of two spinless isospinor fields ϕ_1, ϕ_2 with hypercharge $Y = 1$. The most general form of the 2HDM potential is

$$\begin{aligned}
V = & \frac{\lambda_1}{2} (\phi_1^\dagger \phi_1)^2 + \frac{\lambda_2}{2} (\phi_2^\dagger \phi_2)^2 + \lambda_3 (\phi_1^\dagger \phi_1) (\phi_2^\dagger \phi_2) \\
& + \lambda_4 (\phi_1^\dagger \phi_2) (\phi_2^\dagger \phi_1) + \frac{\lambda_5}{2} (\phi_1^\dagger \phi_2)^2 + \frac{\lambda_5^*}{2} (\phi_2^\dagger \phi_1)^2 \\
& + \left[\lambda_6 (\phi_1^\dagger \phi_1) (\phi_1^\dagger \phi_2) + \lambda_7 (\phi_2^\dagger \phi_2) (\phi_1^\dagger \phi_2) + \text{h.c.} \right] \\
& - \frac{m_{11}^2}{2} (\phi_1^\dagger \phi_1) - \frac{m_{22}^2}{2} (\phi_2^\dagger \phi_2) - \left[\frac{m_{12}^2}{2} (\phi_1^\dagger \phi_2) + \text{h.c.} \right]
\end{aligned} \tag{1}$$

Its coefficients are restricted by the requirement that the potential should be positive at large quasiclassical values of ϕ_i (*positivity constraints*). We assume also that these coefficients are not too big so that one can use estimates based on the lowest non-trivial approximation of the perturbation theory.

After EWSB the 2HDM contains 3 neutral Higgs bosons $h_a \equiv h_{1,2,3}$, in generally with indefinite CP parity, and charged Higgs boson H^\pm with masses M_a and M_\pm , respectively¹.

2.1 Reparametrization freedom.

2HDM describes system of two fields with identical quantum numbers. Therefore, its description in terms of original fields ϕ_i or in terms of their linear superpositions ϕ'_i are equivalent; this statement verbalizes the *reparameterization* (RPa) freedom of the model. The RPa group consists of RPa transformations $\hat{\mathcal{F}}$ of the form:

$$\begin{aligned}
\begin{pmatrix} \phi'_1 \\ \phi'_2 \end{pmatrix} &= \hat{\mathcal{F}}_{gen}(\theta, \tau, \rho) \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix}, \\
\hat{\mathcal{F}}_{gen} &= e^{i\rho_0} \begin{pmatrix} \cos \theta e^{i\rho/2} & \sin \theta e^{i(\tau+\rho/2)} \\ -\sin \theta e^{-i(\tau+\rho/2)} & \cos \theta e^{-i\rho/2} \end{pmatrix}.
\end{aligned} \tag{2}$$

This transformation induces a transformation of the parameters of the Lagrangian in such a way that the new Lagrangian, written in fields ϕ'_i , describes the same physical content. We refer to these different choices as - the different RPa bases. A subgroup of the RPa group – the rephasing group RPh – describes a freedom in choice of the relative phase of fields ϕ_i .

Transformation (2) is parameterized by angles θ, ρ, τ and ρ_0 . The parameter ρ_0 describes an overall phase transformation of the fields. Since it does not affect the parameters of the potential, it can be ignored. The parameter ρ describes the RPh symmetry of system.

¹The numbering of h_a does not correspond to an order of masses M_a .

The $U(1)_{EM}$ symmetry preserving ground state of this system is given by a minimum of the potential

$$\langle \phi_1 \rangle = \begin{pmatrix} 0 \\ v_1/\sqrt{2} \end{pmatrix}, \quad \langle \phi_2 \rangle = \begin{pmatrix} 0 \\ v_2 e^{i\xi}/\sqrt{2} \end{pmatrix}, \quad (3)$$

with standard parameterization $v_1 = v \cos \beta$, $v_2 = v \sin \beta$.

2.2 Higgs basis

We use below the RPa basis with $v_2 = 0$ (the Higgs, or Georgi, basis [6]), in which the 2HDM potential can be written in the form [7]

$$\begin{aligned} V_{HB} = & M_{\pm}^2 \left(\Phi_2^\dagger \Phi_2 \right) + \frac{\Lambda_1}{2} \left(\Phi_1^\dagger \Phi_1 - \frac{v^2}{2} \right)^2 + \frac{\Lambda_2}{2} \left(\Phi_2^\dagger \Phi_2 \right)^2 \\ & + \Lambda_3 \left(\Phi_1^\dagger \Phi_1 - \frac{v^2}{2} \right) \left(\Phi_2^\dagger \Phi_2 \right) + \Lambda_4 \left(\Phi_1^\dagger \Phi_2 \right) \left(\Phi_2^\dagger \Phi_1 \right) \\ & + \left[\frac{\Lambda_5}{2} \left(\Phi_1^\dagger \Phi_2 \right)^2 + \Lambda_6 \left(\Phi_1^\dagger \Phi_1 - \frac{v^2}{2} \right) \left(\Phi_1^\dagger \Phi_2 \right) + \Lambda_7 \left(\Phi_2^\dagger \Phi_2 \right) \left(\Phi_1^\dagger \Phi_2 \right) + \text{h.c.} \right]. \end{aligned} \quad (4)$$

For this basis we use capital letters to denote fields and parameters of potential, Φ_i and Λ_j respectively.

2.3 Relative couplings

In the discussion below we use the relative couplings for each neutral Higgs boson² h_a ($a = 1, 2, 3$):

$$\chi_a^P = \frac{g_a^P}{g_{SM}^P}, \quad \chi_a^\pm = \frac{g(H^\pm H^- h_a)}{2M_{\pm}^2/v}, \quad \chi_a^{H^+W^-} = \frac{g(H^+W^- h_a)}{M_W/v}. \quad (5)$$

The quantities χ_a^P (where $P = V(W, Z)$, $q = t, b, \dots$, $\ell = \tau, \dots$) are the ratios of the couplings of h_a with the fundamental particles P to the corresponding couplings for the would be SM Higgs boson with $M_h = M_a$. The other relative couplings describe interaction of h_a with the charged Higgs boson H^\pm . Couplings χ_a^V and χ_a^\pm are real due to Hermiticity of Lagrangian, and are directly measurable. Couplings $\chi_a^{H^+W^-}$, χ_a^q and χ_a^ℓ are generally complex.

There are useful sum rules among these couplings, namely

$$(a) \sum_a (\chi_a^V)^2 = 1, \quad (b) (\chi_a^V)^2 + |\chi_a^{H^+W^-}|^2 = 1. \quad (6)$$

Both real and imaginary parts of Yukawa couplings χ_a^q and χ_a^ℓ can be measured in principle, using distributions of Higgs bosons decay products $h_a \rightarrow \bar{q}q$, $h_a \rightarrow \bar{\ell}\ell$. The absolute value of the coupling $\chi_a^{H^+W^-}$ is well measurable, it is fixed by the sum rule (b).

²We omit the adjective "relative" below.

The unitarity of the rotation matrix describing transition from components of fields ϕ_i to the physical Higgs fields h_a , allows to obtain following relations for couplings $\chi_a^{H^+W^-}$ (the factor $e^{i\rho}$ represents the rephasing freedom in the Higgs basis):

$$\begin{aligned}\chi_1^{H^+W^-} &\equiv \left(\chi_1^{H^-W^+}\right)^* = -e^{i\rho} \frac{\chi_1^V \chi_2^V - i\chi_3^V}{\sqrt{1 - (\chi_2^v)^2}}, \\ \chi_2^{H^+W^-} &\equiv \left(\chi_2^{H^-W^+}\right)^* = e^{i\rho} \sqrt{1 - (\chi_2^v)^2}, \\ \chi_3^{H^+W^-} &\equiv \left(\chi_3^{H^-W^+}\right)^* = -e^{i\rho} \frac{\chi_2^V \chi_3^V + i\chi_1^V}{\sqrt{1 - (\chi_2^v)^2}}.\end{aligned}\tag{7}$$

2.4 Minimal set of observables

In ref. [7] a minimal complete set of directly measurable quantities defining the 2HDM (*observables*) was found ($a = 1, 2, 3$):

$$\begin{aligned}&v.e.v. \text{ of Higgs field } v = 246 \text{ GeV}; \\&\text{masses of Higgs bosons } M_a, M_{\pm}; \\&2 \text{ out of 3 couplings } \chi_a^V; \\&3 \text{ couplings } \chi_a^{\pm}; \\&\text{quartic coupling } g(H^+H^-H^+H^-).\end{aligned}\tag{8}$$

In the most general 2HDM, these observables are independent of each other. In particular variants of 2HDM additional relations between these parameters may appear.

The parameters of potential in the Higgs basis are expressed through these observables and free parameter ρ , (appeared in $\Lambda_{5,6,7}$ via couplings $\chi_a^{H^+W^-}$):

$$\begin{aligned}\Lambda_1 &= \sum_a (\chi_a^V)^2 M_a^2 / v^2; & \Lambda_4 &= (\sum_a M_a^2 - M_{\pm}^2) / v^2 - \Lambda_1; \\ \Lambda_5 &= \sum_a (\chi_a^{H^-W^+})^2 M_a^2 / v^2; & \Lambda_6 &= \sum_a \chi_a^V \chi_a^{H^-W^+} M_a^2 / v^2; \\ \Lambda_3 &= 2(M_{\pm}^2 / v^2) \sum_a \chi_a^V \chi_a^{\pm}; & \Lambda_7 &= 2(M_{\pm}^2 / v^2) \sum_a \chi_a^{H^-W^+} \chi_a^{\pm}; \\ \Lambda_2 &= 2g(H^+H^-H^+H^-).\end{aligned}\tag{9}$$

The parameters of the potential (1) with the defined values of $\tan\beta$ and ξ (3) are obtained from parameters (9) with the aid of transformation (2) of the form

$$\begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} = \hat{\mathcal{F}}_{HB} \begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix}, \quad \hat{\mathcal{F}}_{HB} = \hat{\mathcal{F}}_{gen}(\theta = -\beta, \tau = \xi, -\rho).\tag{10}$$

3 Conditions for a CP conservation

In fact, the C-parity is not defined for the system of spinless particles, for such system only P-parity is defined. When in addition we consider fermions, the P-parity violation is transformed to the CP violation (see e.g. [4, 5]).

In the CP violated case a transition like $h_a \rightarrow \bar{q}_1 q_1$ leads to the fermion state with indefinite CP parity (mixture of CP-even and CP-odd components). Therefore, transitions $\bar{q}_1 q_1 \rightarrow h_a \rightarrow \bar{q}_2 q_2$ violate the CP symmetry and CP-odd states can be transformed into CP-even ones and vice versa. This very opportunity is treated as the CP violation.

3.1 General observations

The CP symmetry is conserved in some model containing Higgs bosons if

- *Each observable physical neutral spinless Higgs boson has definite P-parity, in 2HDM – P-even h_1, h_2 and P-odd h_3 .* (11a)

- *There are no P-violating interactions between these scalars.* (11b)

In the standard notations used for 2HDM, P-even scalars h_1, h_2 are denoted h, H and P-odd h_3 is called A . Point (11b) means an absence of the interactions

$$h_i h_j h_3, \quad h_3 h_3 h_3, \quad h_i h_j h_k h_3, \quad h_i h_3 h_3 h_3 \quad (i, j, k = 1, 2). \quad (12)$$

It is well known that in the 2HDM this criterium is fulfilled if

The RPa basis exists in which:

- *all parameters of potential are real;* (13a)

- *relative phase (3) $\xi = 0$.* (13b)

It is worth mentioning, that the condition (13a) forbids an explicit CP violation while conditions (13a) and (13b) together forbid a spontaneous CP violation.

The equation (11) only describes CP-conservation, but does not provide a criterium for CP conservation (or violation). The description (13) is RPa basis-dependent.

3.2 Method of the CP-odd basis-independent invariants

To obtain criterium for CP violation many authors constructed the RPa basis-invariant CP-odd combinations of parameters of the Higgs potential. Then a condition for CP conservation is formulated as a demand of vanishing of all these invariants. For 2HDM three such invariants $Im\mathcal{J}_{1,2,3}$ were found in ref. [8], for multi-Higgs models such invariants were constructed in ref. [14].

The invariants [8] for 2HDM were expressed via measurable quantities in ref. [9]. In the terms of quantities (8), the corresponding conditions for the CP conservation read as

$$\begin{aligned} Im\mathcal{J}_1 &= \sum_{i,j,k} \varepsilon_{ijk} \frac{2M_i^2 M_{\pm}^2}{v^4} \chi_i^V \chi_k^V \chi_j^{\pm} = 0, \\ Im\mathcal{J}_2 &= 2\chi_1^V \chi_2^V \chi_3^V \sum_{i,j,k} \varepsilon_{ijk} \frac{M_i^4 M_k^2}{v^6} = 0, \\ Im\mathcal{J}_{30} &= 4 \sum_{i,j,k} \varepsilon_{ijk} \frac{(M_{\pm}^2 \chi_i^{\pm} + M_i^2 \chi_{\pm}^V) M_i^2 M_{\pm}^2}{v^6} \chi_j^V \chi_k^{\pm} = 0. \end{aligned} \quad (14)$$

Note that in the discussed approach there are four CP-odd invariants and one should check vanishing only of two of them (see e.g. [5]). Since the choice of these two is not fixed from beginning, the presented set contains three conditions, instead of necessary two. Besides, in our opinion the equations (14) are too complicated and their experimental verification, discussed in [9], requires too complex procedure.

3.3 A direct criterium for CP conservation

We formulate conditions for CP conservation without using an intermediate CP-odd RPa-invariants. We start with a description of CP conservation (11) and use only observables.

In Refs. [11], [12] we describe limitation for CP violation, based only on one condition³ (11a), without checking up of condition (11b), in the form

$$\prod_a \chi_a^V = 0, \quad \prod_a \chi_a^\pm = 0, \quad \left| \prod_a \chi_a^f \right| = \prod_a |\chi_a^f|. \quad (15)$$

Below we simplify these conditions and to prove that the set of new conditions is *necessary and sufficient* one.

- **The direct criterium.**

In the CP conserved case all h_a should have definite parity. In particular, one of them is P-odd, while two others are P-even (11a). Therefore, the necessary condition for a CP conservation is an existence of one neutral Higgs boson (we denote it h_3), which doesn't couple to the CP-even states VV and H^+H^- :

There exists a neutral Higgs boson h_3 for which
 $g(h_3VV) = 0, \quad g(h_3H^+H^-) = 0.$

(16)

Now, one has to check condition (11b). In order to do this, we substitute Eq-s. (16), (7) into (9), choosing $\rho = 0$. One can see that all parameters of potential Λ_a in the Higgs basis are real. Therefore, in view of a statement (13), the CP-symmetry of model is not violated. In particular, the CP violated interactions (12) don't appear. (Besides, it is easy to check that conditions (16) ensure compliance of conditions (14) and first two conditions (15).) Therefore we conclude that **the conditions (16) are necessary and sufficient** for establishing CP conservation in the 2HDM.

- **A discussion of a direct criterium.**

It is worth to note, that the condition $g(h_3VV) = 0$ means that the scalar h_3 has no P-even admixture. This results immediately to the identities $g(h_3h_kZ) = 0$

³Particular version of such approach was used in [13].

($k = 1, 2$). This conclusion allows to replace checking up of the condition $g(h_3VV) = 0$ by checking of one of conditions $g(h_3h_kZ) = 0$, i. e. non-observation of corresponding decays, as it was proposed⁴ in [13].

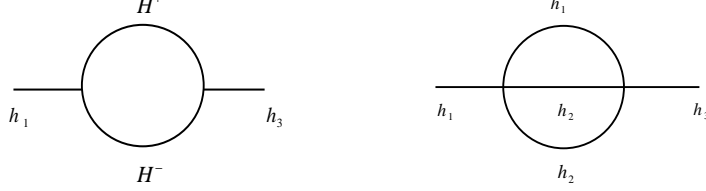


Figure 1: *Mixing obliged by the H^+H^- loop (left) and one of CP violated vertices (12) (right).*

If $g(h_3H^+H^-) \neq 0$, the loop diagrams of Fig.1 mix the Higgs states with different incident CP parity, resulting in CP breaking.

- **Consequence for the Yukawa interaction.**

The Yukawa interaction can violate CP symmetry of the model only in the case of a P non-conservation for scalars. The conditions (16) guarantee that h_a are pure state of CP parity (h_1 and h_2 are CP even, h_3 is CP odd). In this case Yukawa interactions cannot generate CP violation, and the third condition (15) is fulfilled automatically.

Certainly, interactions of fermions, different from the Yukawa interaction with Higgs particles, can violate CP due to some other mechanisms; for example the CKM matrix describes such outer violation. Such violation can be transferred to the Higgs sector, presumably as a small correction. To observe this kind *induced* CP violation, the last condition of (15) should be checked

$$\left| \prod_a \chi_a^f \right| = \prod_a |\chi_a^f| \quad \text{for each fermion } f. \quad (17)$$

4 Possibilities for a verification

The verification of CP conservation requires an observation of all scalars of the model. In the realized in Nature SM-like scenario this looks difficult (see e.g. [12]). Moreover, one should check that some measurable quantities are equal 0. In any case, these measurements cannot pretend for a high accuracy. From this point of view the proposal to change a direct criterium to a condition for a non-observation of decay $h_3 \rightarrow h_1Z$, etc. given in [13] looks attractive. Nevertheless, one cannot expect high accuracy in the statement about CP conservation in the 2HDM.

One can imagine the situation in which CP violation is concentrated in the coupling $g(h_3H^+H^-) \neq 0$ and interactions (12) while $g(h_3VV)$ and $g(h_3h_kZ)$

⁴Let us remind that such condition (including all its forms discussed in [13]) is insufficient to establish CP conservation in the considered model in the general case, since does not guarantee the fulfillment of the condition (11b), i. e. non-appearance of CP odd vertices (12)

are small (e. g. if they appear only at the loop level). In such case, due to experimental inaccuracy, measuring only the latter couplings can not give information about CP violation in the model.

5 Conclusions

We present here the new, necessary and sufficient conditions for CP conservation in 2HDM (16), which are common for all mechanisms of CP violation. We prove that the verification of CP conservation in 2HDM requires to measure two simple and relatively easily testable observables instead of three more complex conditions (14) discussed by many authors [9], [8].

Appendix. Necessary condition for CP conservation in Multi Higgs Doublet Model

The criterium of CP conservation in the Multi Higgs Doublet Models – nHDM are also of interest. Here, the method of CP-odd invariants allows to construct many equations, which can be used for obtaining conditions for CP conservation. Both complete set of these equations and their expressions via measurable quantities are absent up to now (see e. g. [14]).

The direct method used above allows to formulate for the nHDM simple necessary conditions for the CP conservation.

After EWSB the nHDM contains $2n - 1$ neutral Higgs bosons h_a , generally with indefinite CP parity, and $n - 1$ charged Higgs boson H_b^\pm with masses M_a , $M_{b\pm}$, respectively. The couplings $h_a VV$ obey first sum rule (6). In the case of CP conservation one can split spinless neutral particles h_a into two groups: P-even h_1, \dots, h_n and P-odd h_{n+1}, \dots, h_{2n-1} . Similarly to (16), the condition for a CP conservation in the nHDM can be written as

$$\boxed{\begin{array}{l} \text{There exist } n - 1 \text{ neutral Higgs bosons } h_c, \text{ for which} \\ g(h_c VV) = 0, \quad g(h_c H_b^+ H_b^-) = 0 \quad (n + 1 \leq c \leq 2n - 1). \end{array}} \quad (18)$$

These $n(n - 1)$ conditions are *necessary* for CP conservation. We don't know now whether these conditions are *sufficient* or not.

Acknowledgments

We are thankful to G. C. Branco, I.P. Ivanov, M. Rebelo, R. Santos for discussions. This work was supported in part by grants RFBR 15-02-05868, NCN OPUS 2012/05/B/ST2/03306 (2012-2016) and HARMONIA project under contract UMO-2015/18/M/ST2/00518 (2016-2019).

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